MAGNETIC RESONANCE COIL ELEMENT WITH EMBEDDED ELECTRONICS MODULE

DESCRIPTION

The following relates to the magnetic resonance arts. It finds particular application in surface coils and surface coil arrays used in magnetic resonance imaging, and will be described with particular reference thereto. However, it also finds application in other types of radio frequency coils used for transmitting radio frequency excitation pulses and for receiving magnetic resonance signals.

Surface receive coils are used in magnetic resonance imaging to obtain good radio frequency coupling with a region of interest. For larger regions of interest, more than one surface coil can be used to provide greater coverage. Moreover, in applications such as sensitivity encoding (SENSE), the coils are used in parallel to image a common region of interest at an increased data acquisition rate.

A problem arises in that radio frequency current induced in one surface coil can couple to neighboring surface coils, producing artifacts or other degradation of the resulting reconstructed image. To address this problem, a pre-amplifier with matching circuitry is commonly used to provide a high output impedance as seen by the coil. Moreover, radio frequency baluns, traps, or the like can be incorporated to further suppress induced currents. Detuning circuitry is generally provided for each coil to detune the coil from the magnetic resonance frequency during the transmit phase of magnetic resonance imaging. Additional monitoring circuitry, safety interlock circuitry, or the like is also optionally coupled to each surface coil. The overall electronics package including, for example, the pre-amplifier and matching circuitry, radio frequency trap, detuning circuitry, monitoring and safety circuitry is commonly arranged in an electronic module.

For optimal operation, the electronic module should be close to the surface coil. However, the electronic module can adversely affect the imaging. For example, some electronic components may produce substantial radio frequency noise or interference. Moreover, ground planes, radio frequency shields, and the like can produce magnetic field flux expulsion effects that can distort the magnetic field in the vicinity of the electronic module and change the coil sensitivity to the magnetic resonance signal. Because of these

and other concerns, the electronic module is generally positioned displaced outside a periphery of the surface coil.

While such displaced positioning of the electronic module improves image quality, it complicates design of surface coil arrays. Lead lines between the coils and their associated electronics provide additional opportunity for coupling and cross-talk. Large surface coil arrays provide large volume coverage. For parallel imaging techniques such as SENSE, a large array of coils can enable higher SENSE factors or otherwise increased data acquisition rates. Large arrays, for example rectangular arrays of N×M coils where N>2 and M>2, have interior coils that are completely surrounded by other surface coils. In such arrays, the interior coils are not readily connected with electronics arranged at the coil periphery.

The present invention contemplates an improved apparatus and method that overcomes the aforementioned limitations and others.

According to one aspect, a radio frequency coil is disclosed. A radio frequency antenna is disposed on a substrate. An electronics module is disposed on the substrate and is electrically connected with the radio frequency antenna.

According to another aspect, a radio frequency coils array is disclosed. A plurality of radio frequency coils are arranged such that the radio frequency antennae of the plurality of radio frequency coils span a coils array surface. Each radio frequency coil includes a substrate, a radio frequency antenna disposed on the substrate, and an electronics module disposed on a central region of the substrate and electrically connected with the radio frequency antenna. The radio frequency antenna includes a conductor disposed on the substrate outside of and at least partially surrounding the central region of the substrate.

According to yet another aspect, a magnetic resonance imaging system is disclosed. A main magnet produces a substantially spatially and temporally constant main magnetic field within a field of view. Magnetic field gradient coils impose selected magnetic field gradients on the main magnetic field within the field of view. A means is provided for applying a radio frequency pulse to the field of view. At least one radio frequency coil is arranged to detect a magnetic resonance signal induced by the applied

radio frequency pulse. The at least one radio frequency coil includes a radio frequency antenna disposed on a substrate and an electronics module disposed on the substrate. The electronics module is electrically connected with the radio frequency antenna.

According to still yet another aspect, a magnetic resonance imaging method is provided. Magnetic resonance is excited in an imaging subject. A magnetic resonance signal is received using one or more radio frequency coils each including a radio frequency antenna disposed on a substrate and an electronics module disposed on the substrate and electrically connected with the radio frequency antenna. The radio frequency antenna of each coil is in proximity to the imaging subject.

One advantage resides in improved compactness of a surface coil for magnetic resonance imaging.

Another advantage resides in reduced external electrical wiring in a surface coil array.

Yet another advantage resides in more adaptable and configurable three-dimensional surface coils array construction.

Numerous additional advantages and benefits will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 diagrammatically shows a magnetic resonance imaging system employing a generally cylindrical radio frequency surface coils array.

FIGURES 2A and 2B shows a side view and an end view, respectively, of the generally cylindrical radio frequency surface coils array of FIGURE 1. In FIGURE 2B, the cable bundles are not shown.

FIGURE 3 diagrammatically shows one embodiment of the radio frequency surface coils of FIGURES 1, 2A, and 2B.

FIGURE 4 diagrammatically shows another embodiment of the radio frequency surface coils of FIGURES 1, 2A, and 2B, in which the electronic module is fabricated on the coil substrate.

FIGURE 5 diagrammatically shows yet another embodiment of the radio frequency surface coils of FIGURES 1, 2A, and 2B, in which the electronic module is separated from the substrate by spacers or standoffs.

FIGURE 6 diagrammatically shows a linear coils array in which the coils partially overlap.

FIGURE 7 diagrammatically shows a 3×4 rectangular coils array in which the coils share a common substrate that includes printed circuit buses providing electrical access to the coils from an edge of the coils array.

With reference to FIGURE 1, a magnetic resonance imaging scanner **10** includes a housing **12** defining a generally cylindrical scanner bore **14** inside of which an associated imaging subject **16** is disposed. Main magnetic field coils **20** are disposed inside the housing **12**, and produce a main B_0 magnetic field directed generally along and parallel to a central axis **22** of the scanner bore **14**. The main magnetic field coils **20** are typically superconducting coils disposed inside cryoshrouding **24**, although resistive main magnets can also be used. The housing **12** also houses or supports magnetic field gradient coils **30** for selectively producing magnetic field gradients in the bore **14**. The housing **12** further houses or supports a radio frequency body coil **32** for selectively exciting and/or detecting magnetic resonances. The housing **12** typically includes a cosmetic inner liner **36** defining the scanner bore **14**.

A surface coil array **40** disposed inside the bore **14** includes a plurality of surface coils **44**. The surface coil array **40** can be used as a phased array of receivers for parallel imaging, as a sensitivity encoding (SENSE) coil for SENSE imaging, or the like. In another approach, the coils **44** image different areas of the imaging subject **16**. The main magnetic field coils **20** produce a main B_0 magnetic field. A magnetic resonance imaging controller **50** operates magnetic field gradient controllers **52** to selectively energize the magnetic field gradient coils **30**, and operates a radio frequency transmitter **54** coupled to

the radio frequency coil **32** or the surface coil array **40** to selectively inject radio frequency excitation pulses into the subject **16**.

By selectively operating the magnetic field gradient coils **30** and the radio frequency coil **32** magnetic resonance is generated and spatially encoded in at least a portion of a region of interest of the imaging subject **16**. By applying selected magnetic field gradients via the gradient coils **30**, a selected k-space trajectory is traversed, such as a Cartesian trajectory, a plurality of radial trajectories, or a spiral trajectory. Alternatively, imaging data can be acquired as projections along selected magnetic field gradient directions. During imaging data acquisition, the magnetic resonance imaging controller **50** operates a radio frequency receiver **56** coupled to the coils array **40** to acquire magnetic resonance samples that are stored in a magnetic resonance data memory **60**.

The imaging data are reconstructed by a reconstruction processor **62** into an image representation. In the case of k-space sampling data, a Fourier transform-based reconstruction algorithm can be employed. Other reconstruction algorithms, such as a filtered backprojection-based reconstruction, can also be used depending upon the format of the acquired magnetic resonance imaging data. For SENSE imaging data, the reconstruction processor **62** reconstructs folded images from the imaging data acquired by each coil, and then combines the folded images along with coil sensitivity parameters to produce an unfolded reconstructed image.

The reconstructed image generated by the reconstruction processor **62** is stored in an image memory **64**, and can be displayed on a user interface **66**, stored in non-volatile memory, transmitted over a local intranet or the Internet, viewed, stored, manipulated, or so forth. The user interface **66** can also enable a radiologist, technician, or other operator of the magnetic resonance imaging scanner **10** to communicate with the magnetic resonance imaging controller **50** to select, modify, and execute magnetic resonance imaging sequences.

With continuing reference to FIGURE 1 and with further reference to FIGURES 2A and 2B, the surface coil array **40** includes a plurality of linear coil arrays **70** each having four, in the illustrated embodiment, surface coils **44** fabricated on a common substrate **72**. In the illustrated surface coil array **40** there are eight linear coil arrays **70**, only four of which are visible in the side views of FIGURES 1 and 2A. Electrical cable bundles **74, 76** (shown diagrammatically in FIGURE 1 and in more detail in FIGURE 2A;

omitted from FIGURE 2B) connect to electronic modules **78** that are disposed on top of each surface coil **44** to provide electrical power, to transmit a signal corresponding to the radio frequency signal received by the coil **44**, and to provide other optional input to and output from the coil **44**. Two additional cable bundles (not shown) substantially similar the cable bundles **74, 76** connect to the four linear coil arrays that are not visible in the side views of FIGURES 1 and 2A. In the embodiment illustrated in FIGURES 1, 2A, and 2B, each linear coil array **70** is substantially planar, and hinged connections **80** connect long edges of the linear coil arrays **70** to define the generally cylindrical coil array **40** which has a hexagonal cross-section as best seen in FIGURE 2B.

With reference to FIGURE 3, one of the radio frequency surface coils **44** is shown in greater detail. FIGURE 3 shows an end coil of one of the linear coil arrays **70**; a broken end **84** diagrammatically indicates continuation of the common substrate **72** to the other surface coils of the linear coils array **70**. The common substrate **72** is generally planar, which plane is flexed into an arc in some embodiments. An electrically conductive film of copper or another electrically conductive material defines a generally planar electrically conductive loop **90** or other conductor shape disposed on the substrate **72** that functions as a radio frequency antenna for receiving a magnetic resonance signal. In one suitable fabrication approach, a copper-coated substrate of plastic or another insulating material is lithographically processed to remove the copper coating from areas of the substrate such that the remaining copper-coated areas define the antenna loop **90** on the substrate **72**. Such lithography is readily applied to the copper coated common substrate to define the four coils of the linear coils array **70**.

The electronics module **78** is disposed on the substrate **72** in a central region **96** of the substrate **72**, with the radio frequency antenna loop **90** outside of and at least partially surrounding the central region **96**. Ends **100** of the antenna loop **90** extend into the central region **96** to electrically connect the antenna **90** with the electronic module **78**. In one embodiment, the electronic module **78** has a width or other lateral dimension (W_{elec}) that is less than or about three-fifths of a width or other lateral dimension (W_{coil}) of the radio frequency antenna **90**. The electronics module contains various electronic components for operating the surface coil **44**, such as a pre-amplifier with matching circuitry, electronic resonance detuning circuitry, monitoring circuitry, safety interlocks circuitry, radio frequency traps or baluns, electric power distribution circuitry, or the like.

The electronics module **78** is separately housed and optionally contains a ground plane and/or a radio frequency shield that produce substantial magnetic flux expulsion. Even if the electronics module **78** does not contain either a radio frequency shield or a ground plane, various radio frequency electronic components contained in the module **78** typically produce some magnetic flux expulsion effects. However, because the antenna loop **90** measures the total radio frequency flux enclosed by the loop **90**, magnetic field distortions in the central region **96** have a limited effect on the magnetic resonance signal received by the antenna loop **90**. As an example, if the lateral dimension (W_{elec}) of the electronics module **78** is about one-half of the lateral dimension (W_{coil}) of the antenna **90**, the loop sensitivity to the magnetic resonance signal is reduced by less than 10%. In order to minimize the effect of flux expulsion, the electronics module **78** should be located close to the center of the central region **96** surrounded by the antenna **90**. The electronics module **78** should be located close to the center of the antenna loop **90**.

In one embodiment, the antenna loop **90** is interrupted by one or more in-line capacitors **104, 106** or other reactive elements, which provide resonance frequency tuning, d.c. current blocking, or other effects. While the single-turn, substantially square antenna loop **90** is illustrated, it will be appreciated that the surface coil can include a multiple-turn antenna loop, a circular or otherwise-shaped antenna loop, or the like. Furthermore, it is contemplated to use a radio frequency antenna topology other than a complete loop, such as one or more electrically conductive fingers extending partway around the central region **96**.

With reference to FIGURE 4, another surface coil **44'** is similar in some respects to the surface coil **44**. The surface coil **44'** is also suitable for use in the coils array **40**. In describing the surface coil **44'**, components that are unchanged respective to the surface coil **44** are labeled using identical reference numbers, while components that are modified respective to the surface coil **44** are labeled using corresponding primed reference numbers.

In the surface coil **44'**, the separately housed electronic module is replaced by an electronics module **78'** that is constructed directly on the central region **96** of the substrate **72**. The electronic module **78'** includes printed circuit traces **110** that are lithographically defined during the lithographic defining of the antenna loop **90**, or by another lithography process. One or more discrete electronic components, such as a

toroidal inductor **112**, a radio frequency signal processing component **114**, and a transmitter circuit **116**, are disposed on the central region **96** of the substrate **72** and are interconnected by the printed circuit traces **110**. In both electronic modules **78, 78'**, it is preferred to use toroidal inductors, solenoidal inductors with balanced turns, or other types of inductors which limit production of stray magnetic fields.

Optionally, one or more components that produce substantial radio frequency noise or interference, such as the radio frequency signal processing component **114**, are enclosed in a radio frequency shield **120**. Other components, such as the inductor **112** and the transmitter circuit **116**, which are "quiet" and do not produce substantial radio frequency noise or interference, are suitably disposed outside of the radio frequency shield **120**. This allows the size of the radio frequency shield **120** to be reduced to a size sufficient to house the noisy circuit components, thus reducing magnetic flux expulsion.

However, it is also contemplated to instead enclose the entire electronic module **78'** in a radio frequency shield. For example, in the surface coil **44** of FIGURE 3, the separate housing of the electronic module **78** can also act as a radio frequency shield for the enclosed electronics.

With reference returning to FIGURE 4, rather than attaching the surface coil **44'** to the electrical cable bundle, it receives electrical power from a battery **124** and transmits a signal corresponding to the received magnetic resonance signal by a transmit antenna **126** operated by the transmitter circuit **116**. A suitable wireless transmission system for wireless transmitting the magnetic resonance signal from the coil **44'** are described in Leussler, U.S. patent no. 5,245,288. Of course, the wireless transmission system can be used with the other embodiments and the cable bundle can be used with the FIGURE 4 embodiment.

With reference to FIGURE 5, another surface coil **44"** is similar in some respects to the surface coil **44** of FIGURE 3. The surface coil **44"** is also suitable for use in the coils array **40**. In describing the surface coil **44"**, components that are unchanged respective to the surface coil **44** are labeled using identical reference numbers. The surface coil **44"** differs from the surface coil **44** principally in that the electronics module **78** is spaced apart from the substrate **72** by spacer elements **130**. The spacers **130** define a separation D_{spc} between the plane of the electronics module **78** and the plane of the radio frequency antenna **90**. In one preferred embodiment, the separation D_{spc} that is about

one-fifth of a lateral width W_{ant} of the antenna **90**, which is sufficient to provide substantial reduction in distortion of the magnetic resonance signal measured by the antenna **90**. A larger separation provides greater reduction of the distortion; however, typically the size of the surface coils array **40**, and hence the size of the separation D_{spc}, is constrained by the bore **14** or by other spatial limitations.

While the surface coils **44, 44', 44"** have been described with reference to the specific coils array **40** shown in FIGURES 1, 2A, and 2B, it will be appreciated that the coils **44, 44', 44"** can be employed singly, or can be employed in arrays with other topologies. In the coils array **40**, a curved array geometry is obtained using generally planar linear coils arrays **70** by use of the hinged connections **80** that allow the planar substrates **72** of some coils **44** to be tilted with respect to the planar substrates of other coils **44**. In another approach for obtaining a curved surface coil, it is contemplated to use a flexible substrate **72** so that the single coil or a coils array constructed from a plurality of coils can flexed or curved.

With reference to FIGURE 6, a linear coils array **140** is constructed of a plurality of radio frequency surface coils **144**, each of which can correspond, for example, to one of the surface coils **44, 44', 44"** shown in FIGURES 3-5. The surface coils **144** do not share a common substrate; rather, each coil **144** has its own substrate. The coils **144** are partially overlapped in the coils array **140**, as shown. Rather than overlapping the coils **144**, the coils **144** can instead substantially abut, or the coils **144** can be spaced apart from one another in the coils array. Moreover, it will be appreciated that a two-dimensional array of coils **144** can be similarly constructed, in which each coil **144** has its own unshared substrate.

With reference to FIGURE 7, a two-dimensional coils array **150** includes a 3×4 array of rectangular coils **154** that share a common substrate **172**. Each of the coils **154** can correspond, for example, to one of the surface coils **44, 44', 44"** shown in FIGURES 3-5. Printed circuit buses **176, 178, 180** are lithographically defined on the substrate **172**, typically during lithographic definition of the antenna loops of the coils **154**. The printed circuit buses **176, 178, 180** provide electrical access to the electronic modules of the coils **154** from an edge **184** of the coils array **150**. The printed circuit buses **176, 178, 180** thus replace the electrical cable bundles **74, 76** of the coils array **40** shown in FIGURE 2A. The coils array **150** can be planar or, if the substrate **172** is made of a flexible

plastic or other flexible electrically insulating material, the coils array **150** may be flexible. In the latter case, the surface coils array **150** may be flexed to better conform with a curved surface of the imaging subject **16**.

Although lithographically patterned films on the substrate **72** have been described, it is also contemplated to use electroplating or the like to form the electrically conductive films described herein. Moreover, while receive coils have been described, transmit coil arrays can be similarly constructed. Still further, while surface coils have been described, head coils and other coils can similarly be constructed with embedded electronics by arranging the electronics with a small magnetic field flux repulsion cross-section and by arranging the electronics near a center of a receive coil loop of the magnetic resonance receive coil.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.